Chapter 1: Introduction

Coal is an important fossil fuel, next to oil and natural gas, in the power industry. It has been used as a main or an alternative source of energy in many countries. The fact that coal is a heterogeneous mixture of organic material and inorganic impurities (which was formed under a slow and continuous transformation of organic material) contributes to the need for coal preparation. The definition of coal preparation, which describes the precombustion clean-up technology, is also commonly termed *coal beneficiation*, coal cleaning, or washing.

The principal consideration of coal beneficiation is to upgrade the quality of coal for direct use in steam and power generation, or for special uses such as chemical feedstock, feed to liquefaction and gasification, etc. The properties and quantities of impurities in coal are known to be the major factors that place limitations on coal utilization. All coals are not the same. They have their physical and chemical structures that are highly variable, as they vary in rank. Thus, the type of coal beneficiation technology and the extent of beneficiation depend mostly on the type of coal, the means of mining, and the clean coal utilization.

The output from any coal mine, in these days, usually consists of raw coal that is wetter and finer, and also contains more impurities than in the past due to: i) mining of lower quality coals, ii) advanced, continuous and non-selective mining techniques that cause more coal being broke up and more impurities being included, and iii) extensive water utilization for minimizing dust (Lockhart, N.C., 1984). While the quality of run-of-mine (ROM) coals is generally decreasing, the necessity for efficient coal beneficiation technology is significantly increasing, resulting in an increased demand for high-quality coals that meet both market and environmental standards.

1.1 Coal Beneficiation

Coal is rarely used as mined. Most is beneficiated or prepared prior to consumption. During the past decades, many coal beneficiation methods that are capable of substantially reducing impurities from coal have been developed and commercialized. The coal beneficiation technologies are generally classified as *physical, chemical and microbial beneficiation techniques.*

Most of the widely used coal beneficiation technologies, in all categories above, are wet processes that involve cleaning, recovery and dewatering of fine particles. To avoid these problems, *dry beneficiation of coal* is considered as an alternative and a promising approach. Indeed, the dry technologies for coal beneficiation, such as pneumatic density separation (air cleaning), have already been used in the past. Unfortunately, none of those dry techniques have been established with great commercial success. Nonetheless, a large number of work and research studies have been made in recent years on dry beneficiation of coal, as the results are encouraging.

Before considering such cases, it is helpful to have a short review of the coal beneficiation methods that are, at present, technically and commercially available. It is important to note that detailed technical descriptions of the reviewed processes are available in the literature and will not be repeated here. Emphasis of the literature will be made on dry coal beneficiation process, particularly on *electrostatic beneficiation of coal*.

1.1.1 Chemical Coal Beneficiation

Chemical coal beneficiation (Chemical Coal Cleaning, CCC) utilizes some chemical processes to separate coal from its impurities. A variety of chemical coal beneficiation processes are under development and some of these processes are also capable of removing organic sulfur from coal, which is beyond the removal ability of any physical beneficiation processes. It is noted that most chemical coal cleaning processes can remove as much as over 90% of pyritic sulfur and several can extract up to 40% of the organic sulfur from the ROM coal. This could result in the total sulfur reduction in the coal in the range of approximately 50-80% (Hutton, C.A. and Gould, R.N., 1982). Furthermore, the chemical cleaning methods recently under development claim that they can also withdraw significant quantities of trace elements and some nitrogen, in addition to the sulfur. However, the physical coal beneficiation methods do remove ash more effectively.

Desulfurization reagent is the most important criteria for successful chemical coal beneficiation processes. The reagent must be selective and not substantially react with the other coal components. Considering the recovery of reagent from coal matrix, the reagent should be regenerable, be either soluble or volatile, and be inexpensive.

Table 1.1 shows the major chemical coal cleaning processes that Khoury (1981) has listed and briefly summarized. The first four processes in the table can remove only pyritic sulfur, whereas the remaining processes assert to achieve amounts of organic sulfur removal, as well as pyritic sulfur removal. The first process, Magnex process, is the only chemical coal beneficiation method that is a totally dry process and has no coal washing and dewatering problems. (Technically, has also been considered a dry physical coal beneficiation process. See section: magnetic separation.) However, among all of these processes, the Meyers process is probably the most advanced with the ability to remove from 80 to nearly 100% of pyritic sulfur from nominally 14 mesh top size coal, according to the test evaluation.

1.1.1.1 Chemistry of Desulfurization Reactions (See details in Meyers, R.A., 1977)

i) Desulfurization of Pyrite:

a) Displacement Reaction

b) Acid Base Neutralization

c) Oxidation Reaction

d) Reduction Reaction

ii) Desulfurization of Organic Sulfur Compounds:

a) Solvent Partition

b) Thermal Decomposition

c) Acid-Base Neutralization

d) Reduction Reaction

e) Oxidation Reaction

f) Neucleophilic Displacement

1.1.1.2 Problems of Chemical Coal Beneficiation Technology

Many concerns created by chemical coal cleaning processes are environmental hazards. Not only does the chemical coal beneficiation present a dust and particulate problem similar to that of physical coal beneficiation, but also the problem is intensified by the high volume of very fine coal sizes handled in these processes (Hutton, et.al., 1982). The handling and disposal of by-products, including the discharge of water and sulfur-containing gas, have yet to be established in an efficient way. Furthermore, the by-products, hot water and sulfur may be found contaminating with coal.

The other problems associated with the chemical coal cleaning processes appear in the engineering area. The major dilemma involves the selection of economical and suitable materials and systems to avoid erosion problem due to exposure of unit equipment to corrosive acid, high pressure and high temperature (Khoury, 1981). In addition, the chemical coal beneficiation processes seem to be expensive and none have been successfully established as a commercial process.

1.1.2 Physical coal beneficiation

Most coal beneficiation techniques are based on the difference in the physical characteristics of coal and its impurities to separate the two. Physical coal beneficiation (Physical

Table 1.1. Summary of Major Chemical Coal Cleaning Processes

Processes	Method	Sulfur Removed	Problems
Maxnex	Dry pulverized coal treated with $Fe(CO)_5$ causes pyrite to become magnetic and removed magnetically.	Up to 90% pyritic	Disposal of sulfur- and S-containing solid residues.
Syracuse	Coal is comminuted by exposure to NH_3 vapor.	50-70% pyritic.	Disposal of sulfur containing residues
Meyers	Oxidative leaching using $Fe_2(SO_4)_3$ + O_2 in water.	90-95% pyritic	Disposal of acidic $FeSO_4$ and $CaSO_4$, sulfur extraction step needs proof.
LOL	Oxidative leaching using O_2 and water at moderate temp and pressure.	90-95% pyritic	Acid corrosion of reactor.
ERDA (PETC, PERC)	Air oxidation and water at high temperature and pressure.	~95% pyritic; up to 40% organic	Gypsum sludge disposal, Acid corrosion at high temperatures.
GE	Microwave treatment of coal permeated with NaOH solution converts sulfur forms.	~75% total S.	Process condition not established, Caustic re-generation not set.
Battelle	Mixed alkali leaching	~95% pyritic; ~25-50% organic	Closed loop regeneration unproven, Na left in coal.
JPL	Chlorinolysis in organic solvent.	~90% pyritic; up to 70% organic	Environmental problems.
IGT	Oxidative pretreatment followed by hydrodesulfurization at 800 ^oC.	~95% pyritic; up to 85% organic	Low BTU yield (<55%), Change of coal matrix.

Coal Cleaning, PCC) processes are ones that remove ash-forming constituents and pyritic sulfur from coals without chemical modification or destruction of the coal or impurities. More than 55% of the coal mined in the United States is beneficiated by a physical cleaning technique (Khoury, 1981). Many physical coal beneficiation processes have been commercially operating, but some advanced processes for fine coal cleaning are still under development. The physical coal beneficiation systems range from simple systems, for just removing coarse impurities, to sophisticated systems designed for more effectiveness in ash and sulfur removal. In a commercial coal preparation plant, the cleaning process is usually confined to physical processes that are based on the difference in the specific gravity and on the difference in surface property of coal and its impurities. The raw coal is typically subjected to sizing and screening, specific gravity-based cleaning, dewatering, clarifying, and drying, respectively. However, a modern coal beneficiation plant does not employ a specific cleaning process. On the contrary, a number of different beneficiation processes are applied either sequentially or in various combination.

1.1.2.1 Wet Physical Coal Beneficiation

As noted earlier, the most widely used coal beneficiation processes are wet processes. Practically, wet physical coal beneficiation methods employ gravity-based concentration to lower the ash-forming impurities and to partially remove the pyritic sulfur present in coal; with the exception of the froth flotation technique. The particular physical characteristics of the coal determine the effectiveness in the reduction of the impurity constituents. The wet physical coal cleaning processes generally used is summarized in Table 1.2.

i) Conventional Wet Physical Coal beneficiation

Jigs

Among the physical techniques, jigs are one of the oldest, and still one of the most common techniques used for coal and mineral ore beneficiation. The basic principle of jigging involves stratifying raw coal by the pulsating fluid (water) that causes expansion and compaction of the coal bed.

Dense-Medium Vessels

By using liquid that has a specific gravity intermediate between the coal and the mineral impurities, dense (heavy)-medium vessels practically separate the coal from the refuse. Of the separating medium employed in this process, magnetite is the most frequently used due to its low cost and recovery ease. The use of this technique is second only to the use of jigs.

Heavy-Medium Cyclone

The heavy-medium cyclones or high-flow dense-medium vessels are one of the simplest and the most efficient techniques for physical coal beneficiation, particularly for the intermediate size coal. In this process, coal is premixed with the heavy medium of specific gravity intermediate between the coal and the mineral impurities and fed to the cyclone. The rate of floating or sinking for fine particles can be increased by using a cyclone or centrifuge. Yet, the effectiveness of this technique is limited by the particle size (Singh and Peterson, 1979).

Wet Concentrating Table

Another one of the oldest and most widely used coal cleaning techniques is the wet concentrating table, a common hydraulic separator. This cleaning device, in accordance with the difference in densities of coal and impurities, separates coal from refuse by shaking raw coal particles across a nearly horizontal surface.

Cone and Spiral Concentrators, Vorsyl and Vor-Siv

Cone concentrator, Spiral concentrator, Vorsyl separator, and Vortex dewatering sieve known as “Vor-Siv,” are the other wet physical beneficiation processes developed for possible -

Table 1.2. Wet Physical Coal Beneficiation (Khoury, 1981)

For coarse coal (8 x 1/4 inch) processing	
	Dense-medium vessels
	Jigs
For fine coal (-1/4 inch x 0) processing	
	Dense-medium cyclone, Hydrocyclone
	Wet concentration tables
	Cone concentrators, Spiral concentrators
	Froth flotation
	Centrifuges (Vorsyl, Vor-Siv)

applications in coal processing. Cone concentrators use the principle of flowing-film concentration, whereas the separations by spiral concentrators, vorsyl separator and Vor-Siv are accomplished by a combination of centrifugal forces and gravitational forces.

It is reported that the efficiency of the cone concentrator is relatively low and requires several runs within a single machine to achieve an effective separation. However, due to its low installation and operating costs, the cone concentrator is still considered a possible alternative to some of the devices currently used, particularly in the area of secondary coal cleaning.

Turning now to the other separators. Spiral concentrators are simple devices for separating pyritic sulfur and ash from coal, but not widely used in the coal preparation. It is suggested that they should be used only along with the other wet methods as a "rougher" cleaning unit.

The other device used extensively in United Kingdom to produce low-sulfur, low-ash coking coal, and to recover anthracite from waste banks, is the Vorsyl separator. The Vorsyl separator shows nearly the same efficiency as conventional dense-medium cyclones. It is a completely cylindrical vessel containing an axially arranged, open-ended vortex finder for removal of clean coal through the base of the chamber.

The Vor-Siv or Vortex Dewatering Sieve, developed by the Polish coal industry, is one of the devices for coal beneficiation. It has been operated in United States since mid of the 1970s. The Vor-Siv combines the operating characteristics found in cyclones, sieve bends, cross-flow screens, and vibrating screens. To date, there is almost no attention paid to the application of the Vor-Siv to the separation of sulfur and mineral matter from raw coal, owing to the more efficient wet methods, such as froth flotation.

Froth Flotation

As the need for the recovery of fine and ultra-fine coal increased, the froth flotation technique was developed to separate the fine coal from the mineral matters. This coal beneficiation technique is a physicochemical process that depends on the difference in surface properties of coal and its mineral impurities (hydrophobic and hydrophilic) to effect the separation. In froth flotation, the coal is selectively attached to air bubbles (with the help of flotation reagent) and can be skimmed off in a surface froth, while the mineral impurities remain in the water. The details of the froth flotation technique have been reported extensively in the literature that is readily approached. Therefore, it will not be discussed here.

ii) Advanced Wet Physical Coal Beneficiation

The advanced physical coal beneficiation technologies are particularly developed as the innovative variations of those conventional processes noted above. The main advantages that the advanced physical coal beneficiation techniques claim to have over the conventional techniques are the higher percentage of ash and pyritic sulfur removal, the more effective fine coal cleaning, and the total cost reduction once the techniques are commercially utilized.

Multi-Stream System

The multi-stream coal cleaning system is a coal beneficiation process advanced to commercially produce a low-sulfur coal, a medium-sulfur coal, and a refuse stream. This technique basically consists of a two-stage, heavy-medium cyclone separation facility (Coal Age, 1976). However, this process requires the raw coal feed that has low organic sulfur content to be reasonably successful.

Froth Flotation Columns

A major attempt has been under way to improve the froth flotation process. The use of flotation columns was introduced as a solution to the entrainment problem, which normally occurs in conventional fine particle flotation technique when the particle size is very small or the coal consists of a large amount of clay. To increase the recovery, several microbubble flotation columns have been further developed.

The principle of these columns is founded on the fact that the bubble size reduction can increase the recovery and that the use of wash water can yield the cleaner products. The *Microcel*™ column developed at Virginia Tech is among the flotation columns based on this principle (Yoon, 1991).

Selective Oil Agglomeration

Selective oil agglomeration is one of the few physical coal beneficiation techniques that can be used to clean and recover the extremely fine-sized coal. The process is based on the premise that the coal particles, essentially hydrophobic in nature, can be readily agglomerated with oily substances in aqueous slurry under agitation. By screening and/or centrifuging, the agglomerates can be separated from the hydrophilic mineral particles that remain suspended in the aqueous phase. (Tsai, 1982) Unfortunately, the major disadvantages of this process are the large amounts of oil consumed and waste disposal.

Otisca-T Process

It is of interest that some heavy organic liquids have been used as cleaning or separating medium, instead of hydrocarbon oils. This is known as the Otisca-T process. The process is based on the same theories that control the process of selective oil agglomeration. Probably, the major advantage of this process is the ease of recovery of the low-boiling separating medium, compared to the high-temperature oil recovery in the selective oil agglomeration process. Other advantages claimed are i) the process can clean both coarse and fine coal effectively without the need for costly size-classification devices and ii) this process yields the low-moisture clean coal (Hutton and Gould, 1982). Although this process does not involve water utilization, it is not a dry process. Moreover, the major drawback of this process is the high initial costs.

Wet High-Gradient Magnetic Separation (Wet HGMS)

The wet high-gradient magnetic separation (HGMS) technique has also been proposed as an advanced method of coal beneficiation. In this process, the pulverized coal slurry (water-based slurry) is fed into a separator where it is subjected to a very strong magnetic field. The separator is basically packed with fine strands of strongly ferromagnetic materials, such as ferritic stainless steel wool matrix. The diamagnetic coal particles, practically nonmagnetic, will be unaffected by the magnetic field and will pass through the separator for further treatment. The paramagnetic materials present in coal slurry, on the other hand, will become magnetized and are attracted to the magnetic materials in the separator.

Further attempts have been made to develop an alternative to water-based slurry. The advanced wet HGMS has been carried out using methanol (Maxwell and Kelland, 1978) and fuel oil (Hucko, 1979) as carrier liquids, due to their lower interfacial tension with the coal particles than water. Not only can both of these liquids be more dispersed, but they can also be re-cycled after the separation. The results showed the comparable inorganic sulfur and ash removal with the results from water-based slurries.

It was also mentioned (Birss and Parker, 1981) that there has been an informal report on the use of liquid nitrogen with the wet HGMS technique for removing inorganic sulfur from the coal. This technique claimed several advantages over other techniques in this area. For instance, the separation is enhanced by the smaller flow viscosity of the liquid than water, and the liquid nitrogen can be used in an integral system which includes cryogenic grinding of the coals, etc. In addition, this technique has shown that it can also facilitate the use of matrices comprising fibers of rare earth metals such as Gd and Tb, which have extraordinarily large magnetization values at cryogenic temperatures.

iii) Problems of wet physical coal beneficiation

As noted earlier, the cleaning, recovery and dewatering of fine particles are accounted as the major difficulty in the wet processes. Moreover, water demand and water pollution are also the major drawbacks of the wet processes. The wet techniques can become incapable in region where water is not economically available or water supplies is restrained relative to the demand, or are low quality. It is noted that the total water requirement for all U.S. coal preparation plants is hundreds of billions of gallons per year (Spaite, 1979).

Although the wet beneficiation processes provide environmental protection by reducing the quantities of sulfur, mineral matters, and other impurities present in coal, the operation associated with these systems may controversially create some potential environmental dilemmas, such as the water pollution and the disposal of refuse. In short, these wet techniques implies the transfer of potential pollutants from one section of the environment to another. Virtually, the waste streams from most wet processing contain primarily two types of water pollutants, suspended materials (solid or liquid) and dissolved substances. The dissolved materials are mostly inorganic elements and compounds leached from the ash fraction during the cleaning process. The most common pollution created by the dissolved substances in wastewater, however, is pH control, which is usually acidic and needs to be neutralized before discharge. The suspended materials in wastewater, if not properly treated before the drainage, can cause a critical problem in surface-water systems (Wahler, 1978). Additionally, these suspended materials, composed primarily of fine coal particles, mineral particles (usually clay), and some trace elements, may suffocate the aquatic life and pollute drinking-water sources.

The disposal of refuse also becomes a potentially serious problem. Coal refuse from the wet coal-beneficiation process, usually includes waste coal, slate, carbonaceous and pyritic shale, and clays associated with coal seam. It is reported that, in the U.S., there are many physical coal beneficiation plants that have to handle an estimated 96 million tons of coal cleaning refuse per year (Anderson, 1975).

Furthermore, the wet beneficiation techniques add a significant amount of moisture on the coal which is a consequent requirement for effective dewatering and drying, resulting in an increase in the initial cost. It is important to bear in mind that in the area where the temperature is below the freezing point of water for part of the year, the excess moisture can make the coal likely to freeze, causing the problems in handling and application.

One potential means to avoid the problems associated with wet processing is to use *dry coal beneficiation processes*.

1.1.2.2 Dry Physical Coal Beneficiation

It is of particular interest that the dry material is nearly always the required-final-product in coal preparation and mineral processing; so that the use of any wet technologies should be irreconcilable in principle, even in places where the water supply is not an issue. Furthermore, not only can the dry beneficiation technology exclude the difficulties associated with the water employment in wet techniques (as noted in previous section), but also it requires lower operation cost and power consumption. In addition, the dry techniques are useful in case of an insufficient difference between component densities, by which a difficult floatability is occurred.

While the advantages of the dry beneficiation process over the wet process have been listed, the deficiency of the dry process should also be pointed out. The perceived disadvantages of the dry technique include demeaning separation and lower capacity, non-routine operation, the lack of flexibility and high sensitivity to changes in feed characteristic (size, moisture, rate), the need for pre-drying and pre-screening into narrow size fractions, and the necessity for dust control and safety (Lockhart, 1984). It is reported, however, that some of these drawbacks are observed also in the wet techniques. The assumption should not be made that the major problems came across in the dry method would be irresolvable. It is suggested that the disadvantage of the dry beneficiation processes is often a consequence of the insufficient information, inferior practice, and/or some extrinsic factors.

In fact, the dry mechanical methods, such as "*air concentration*" or "*pneumatic cleaning*," and "*electrostatic separation*," have been used commercially in the past. Unfortunately, the interest in using the dry techniques has declined steadily, despite their lower costs, since the moisture content of run-of-mine coal has increased and the beneficiation efficiencies of wet techniques have been relatively greater. In spite of the decline, some dry beneficiation technologies have competitively gained more attention with new fascinating developments made in recent years.

The following sections are concerned with dry separation using *mechanical, magnetic and electrical techniques.*

i) Mechanical Separation

In coal preparation and mineral processing, mechanical separation involves the response of particles to gravitational, inertial, or centrifugal forces, while in the presence of at least one other force which is usually the viscous drag of fluid. Therefore, the attributes, such as the particle size, shape, density, the fluid viscosity, density, and the solid load in fluid suspension, are all the factors for the bearing of mechanical separation. In principle, most dry mechanical separations are still based on the difference in densities of the components. However, the air-based 'density separations,' compared to the wet equivalent techniques, are evidently less efficient and more sensitive to the feed size.

Screenings and Classifiers

Screening is the simplest size-classification technique and the only one that is not dependent on the particle density. An important progress in industrial screening is the 'Rotating Probability Screen,' developed by the British National Coal Board. With the centrifugal force, the particles are moved along a rotating spoked wheel, increasing gaps from the hub to the outside (Beeckmans and Hill, 1983).

Dry size classifiers includes the aerodynamic classifiers of different mechanisms; namely inertial, free or forced vortex, counter-current, and cross-flow classifiers. Some classifiers may use the combination of the mechanisms. The air classifiers are most practiced for particle sizes below the limits of industrial screening. Practically, the feed size has to be compatible with the product size range desired. Both size range and particle density are generally the 'cut points' for commercial use of classifier. Therefore, due to the dependence on density as well as size, it implies that many devices that are basically classifiers can also be used as beneficiation devices.

Pneumatic Tables and Jigs

It is likely that air jigs are the only pneumatic separators of commercial significance. Pneumatic tables are relatively in less use due to the requirement of closer sized feeds, lower throughputs, and the need of lower surface-moisture feeds. The principles of pneumatic tables and jigs are similar to those of wet tables and jigs, except that, instead of water acting as the separation medium, a blast of air takes an action. The difference in settling velocities of particles in air serves as a basis of the separation in both devices. The pneumatic table has recently seized a development and given good results in dry coal beneficiation (Ditzler and Gross, 1982).

Unlike those of pneumatic tables, the dry table developed by the FMC Corporation uses no air flow, but vibration and gravitational forces, with the feed material behaving somewhat like an autogenous medium (Wilson, 1976). The table can operate over a wide size range. However, it is reported that this device is relatively less efficient compared to the pneumatic table or jig.

Air-Fluidized Particle Bed

Air-fluidized particle bed is theoretically noted as the most promising approach to dry mechanical beneficiation of coal (Lockhart, 1984). However, the method has been applied occasionally to coal beneficiation since it was first illustrated. Furthermore, no large-scale commercial uses seem to have been reported.

In this dry mechanical separation process, the apparent fluid density reflects the density of the solid particles and their volume fraction or voidage. Once a fluidizing medium, basically magnetite, sand, or the mixture of both for coal beneficiation, is chosen of narrowly sized particles that are preferably finer than the to-be-separated feed size, the separation then depends thoroughly on density.

Nonetheless, one of the difficulties in this process is that the fluidizing air velocity has to be maintained above the minimum needed to fluidize the largest particles, and yet still below the limit that would drive the finest particles out of the bed.

The air-fluidized particle bed developed by Warren Spring Laboratories has combined the characteristics of fluidization with that of the vibrating table (Douglas, et.al., 1972). The device has been exercised to coal beneficiation with the use of magnetite as the fluidizing medium. The other air-fluidizing device, also developed by the same company, is the dry 'pinched sluice.' This device was contrived to beneficiate coal and minerals in finer size fraction. It is reported that the pinched sluice gave good results for coal and several minerals. However, according to Butcher and Symonds (1981), there have been no details of their perceptible uses in industry, even the commercial versions of both devices are available.

There are more recent developments in coal beneficiation involving air-fluidization, such as a 'slotted pinched sluice' (Laskowski and Lupa, 1979), a 'dry-flo (pneumatic sluice) separator' (Carta et.al., 1982), a 'downflow-fed fluidizer' (Babari and Gupta, 1980). Unfortunately, none of these devices has been reported as to having any commercial applications. The details of these devices can be found in the literature.

Counter-Current Fluidized Cascade

The counter-current fluidized cascade (CFC), devised by Germain and his co-workers at the Coal Mining Research Center in Canada (CMRC) (Germain et.al., 1982), has been referred as the most recent development in dry fluidized separators (Lockhart, 1984). In the CFC, the vertical partial segregation is observed in a fluidized particle bed when the fluidizing air is at a velocity moderately above the minimum needed. The segregation is enhanced by the use of "counter-current enrichment principle," in which small differences in composition between liquid and vapor phases in a fractional distillation column are used to yield large differences in composition between the boiler and the condenser outlet. This is accomplished by the opposite horizontal movements created in the upper and lower levels of the fluidized bed by means of a baffled endless chain moving across the lower part of the bed, in which a re-compassing of partially separated components occurs.

The CFC system has been tested using limestone, or sand mixed with magnetite or hematite, as a fluidizing medium to separate coal and impurities in the size range 25 x 0.6 mm. of feed particles. For the fines in the range 3.0x 0.1 mm., the authors used the fine raw coal as its own fluidizing medium. The test results showed that the CFC was as good as a heavy medium separator for the feed size 25 x 0.3 mm. and its performance was close to that of wet jig for 3 x 0.6 mm. In comparison with the other pneumatic separators, the authors claimed the CFC to be the only device in this area that has been developed to utilize the internal recycle phenomenon. For this reason, the CFC should be more efficient and can be competitive with the other beneficiation techniques. It was chosen by some reviewers (Butcher and Symonds, 1981) to be the most promising technique in this field for full-scale development.

ii) Magnetic Separation

The origins of the magnetic separation technique are closely associated with the mineral processing technique. It was well documented that the first patent in this field was filed as early as 1792, concerning the concentration of iron ores (Birss and Parker, 1981). In 1958, a report was published of the first attempt to apply the magnetic separation to coal cleaning (Yurovsky and Remesnikov, 1958). Since then, a variety of studies have been undertaken using the magnetic separation technologies in coal beneficiation processes. The key to the magnetic separation technology is the differences between the magnetic susceptibility of particles in feed materials.

It is recognized that coal is weakly diamagnetic, essentially non-magnetic, while most of the mineral matters present in coal, particularly the iron-containing material such as pyrite, are weakly to moderately paramagnetic. Such paramagnetic materials are much more weakly susceptible to the influence of applied magnetic fields than are the ferromagnetic materials, in which a considerable magnetic moment is induced even by weak magnetic fields. The paramagnetic materials do not reach a saturation magnetization value even in the high magnetic fields and, indeed, their magnetic moments increase linearly with applied magnetic fields. Accordingly, the mineral impurities in coal require a strong magnetic-force density sufficiently to attract very weak paramagnetic materials or very fine particles of ferromagnetic or paramagnetic, in order to be separated from coal.

The efforts to beneficiate coal effectively by dry magnetic separation technology have enlarged in the last decades. Tremendous modeling and experimental studies of such technology has applied to coal beneficiation processes and various dry magnetic separation techniques have been accordingly established.

The Magnex Process (Kindig, 1979)

The Magnex process is a dry and low-intensity magnetic beneficiation technique wherein pulverized coal is treated with iron carbonyl [$Fe(CO)_5$] vapor, which magnifies the magnetic susceptibility of the ash and the inorganic sulfur, but leaves the coal unaffected. The treated coal is then subjected to a conventional low-intensity magnetic separator.

The results from the bench-scale studies on coals by using this process showed that the pyritic sulfur and ash contents of the coals were reduced by ~ 86% and 67%, respectively. However, a major problem in this process is the use of iron carbonyl, which is highly toxic and expensive.

Dry High-Gradient Magnetic Separation (Dry HGMS)

Dry HGMS techniques have been used commercially for some considerable time. However, the emphasis of the use of conventional dry HGMS techniques has been on the mineral processing, particularly the concentration of the weaker magnetic iron-bearing minerals. The most widely used of the established commercial devices in this field are the induced roll separators and the Frantz Ferrofilter (Birss and Parker, 1981). The latter is a flexible device which can operate for wet or dry separation. More details about these devices are available in the literature.

The HGMS techniques have been subsequently applied to coal beneficiation because of their prominent technical performances demonstrated in kaolin application. The wet HGMS was first successfully adapted in 1973 in a bench-scale study to remove sulfur and ash from a fine Brazilian coal suspended in water (Trindade, 1973). The application of dry HGMS to coal beneficiation has been initiated in 1976 and first reported by General Electric Company and Massachusette Institute of Technology (Luborsky, 1977). Further studies were carried out since 1978 by Oak Ridge National Laboratory (ORNL) (Hise, et.al., 1979) and by Auburn University (Liu, et.al, 1978).

At the same time, there has been considerable attention to another HGMS process for coal beneficiation, "the magnetic treatment of solvent refined coal (SRC)." This SRC process, technically included in the wet HGMS, involves the use of a volatile coal-derived organic solvent as a carrier liquid and the use of strong magnetic field applied to a stainless steel matrix. After the separation process, the solvent is removed from the product by flash evaporation. A number of investigators (HRI, Inc., 1976; Liu and Lin, 1976; Maxwell and Kelland, 1978) claimed that this process can remove more than 90% of the inorganic sulfur and 25-40% of the ash. Note that both dry and wet HGMS studies on coal beneficiation have been engaged primarily in removing sulfur, particularly pyrite, since the sulfur reduction has been a major concern in US coals.

The key processing concept of HGMS features the difference in magnetic susceptibility of materials, described in the previous section, and the placement of a fine filamentary structure of ferromagnetic material, such as stainless steel wool, knitted wire screen, or expanded metal discs, within a reasonably uniform-high-intensity magnetic field. Such filamentary ferromagnetic material is the source of the field gradient. The slightly magnetic mineral matters are drawn into the field and are trapped on the filaments, while the coal, unaffected by the magnetic field, passes through the system. The dry HGMS technique is similar to the wet HGMS in principle, except no water is involved in the beneficiation process and the magnetic field is applied to an air-fluidized bed of coal particles, or an air-flow separator, rather than a coal slurry container.

According to Birss and Parker (1981), the results for the first study on dry HGMS of coal, carried out by GE in association with MIT, were unsatisfactory. However, these results provided an important finding, which has been confirmed by most of later works. The ultra-fine particles present in the feed are counterproductive to the dry HGMS of coal. Apparently, the ultra-fines are the major source of adhesion between the larger particles, resulting in the promotion of the particle agglomeration and the plugging of the agglomerates to the fine filamentary matrix. The removal of the fines, from below 10 ìm to below 75 ìm, is, hence, required prior to the separation. Oak Ridge National Laboratory (ORNL) carried out a number of tests by adopting a dry gravity feeding of the coal, along with an air-entrained flow or assisted by vibration, to the HGMS matrix. As an extension of this work, a pilot scale continuous "Carousel" separator was developed by ORNL in collaboration with Sala Magnetics, Inc., involving rotary filamentary separation systems known as "Carousel" systems marketed by Sala.

As a way to evade the need for prior removal of the ultra fines from the feed, the "fluidized bed/HGMS matrix" technique was proposed by Auburn University with support from ONRL. A controlling air velocity was used to fluidize the particles, in such a way that the fines were entrained through and out of the "fluidized bed/HGMS matrix" to present as a top clean coal product, while the coarser sizes were maintained in the fluidized state for a sufficient residence time inside the matrix, allowing the magnetic particles in coal to be captured and retained by the matrix. Toward the end of the desired beneficiation period, the magnetically cleaned coal was collected as a bottom clean coal product. However, no scale-up or full-scale viability data have been presented.

The fluidized bed/HGMS has also been developed by Japanese researchers (Kunisue, et.al., 1983) to treat small quantities of the coal (7 %ash). The results appeared to be unattractive for the particle sizes > 210 µm or > 40 µm, while the best results were obtained with the size fraction 105-210 µm (33% ash reduction and 86% coal recovery).

Dry Open Gradient Magnetic Separation (OGMS)

OGMS is a similar coal beneficiation technique, but less publicized and at a less-developed stage than HGMS. This technique was initially developed by the ORNL with the use of the well-known Frantz Isodynamic Laboratory Separator (Open Gradient Separator). In OGMS, a stream of the particles are fed, either by vertical free fall or on a vibrating tray, through a high-gradient magnetic field (much smaller magnetic force than in HGMS) that attracts the refuse materials and deflects clean coal particles, according to their magnetic characteristics. Since there is no trapping, OGMS can operate continuously by splitting the product coal stream and refuse stream into their located exit channels.

According to Lockhart (1984), the OGMS can also perform selectively concentrating the susceptible macerals for the purpose of coal liquefaction. From the test results carried out by ONRL, it was confirmed that the vitrinite content was highest in the diamagnetic fractions while the inertinite and minerals concentrated in the paramagnetic fractions.

iii) Electrical Separation

General Principles

In looking at the development of the technology, it is necessary to establish a reference beforehand. There have been the comprehensive reviews made by a number of authors (i.e. Ralston, 1961; Inculet, 1984; Moore, 1973). However, the collection of works relevant to electrical separation, particularly to *electrostatic coal beneficiation*, is small compared with that in wet separations like froth flotation, or even in magnetic separation.

The electricity phenomenon has its long history, which dates back to more than 2,000 years ago. At that time, people discovered the static charge from rubbing amber with fur or cloth and the charge on the amber was capable of attracting lightweight objects. The concept of this circumstance was not understood until much later. We now know that the amber was frictionally charged to produce "*triboelectricity*." Although the field of electrostatics is one of the oldest electrical sciences, its theoretical information has not been completely established.

As the mechanical separation technique is seemingly effective down to particles 1 mm in size, the magnetic and electrical separation techniques are, instead, most applicable to the fines below 1 mm. In electrostatic separation, it is reported that any ore to be treated must be fine enough to liberate particles of the various phases present in ore (Inculet et.al, 1980).

Electrostatic separation was first introduced to mineral processing in the late 1800s. The first practical separator for minerals, developed by Blake and Morscher (1899), was patented in 1899. Soon afterwards, several other electrostatic separators had made their debuts to the separation industry, and all were patented. The very early processes were basically used for the separation of high conductive gold and metallic sulfides from low conductive siliceous gangue. These early separators usually consisted of a rotating metal drum over which the material was fed and subjected to a high voltage electric field, and a corona discharge. During that time, the best known commercial separator was probably the "Huff separator," which was used for minerals and coal beneficiation (Johnson, 1938).

However, it was not until the demand for mineral beneficiation increased dramatically in the 1940s that the major advances in electrostatic separation and its application emerged. The intermission of the developments in early of this century occurred due to the arrival of flotation. The re-interest in electrical techniques began with the application for rutile beneficiation. Since then, the use of this technique extended to other minerals and coal, respectively. During that time, the development of new electrostatic separation devices was invigorated and the Carpenter's beam-type electrode separator became the basis for all the high tension separators in use today (Carpenter, 1949; 1951; 1965; 1970).

Fundamentally, dry electrical separation involves the interaction between the external electric field and the charging of particles. The separation depends on the motion of particles according to their charges in an electric field, which in turn depends on the particle-charging method and the charging ability of the particles to be separated. Knoll and his co-authors (1988) remarked that the way these opposite charges occur when a particular separation occurs is a common key to distinguish one form of electrostatic separation from another. The electrical separation where there is a charge transfer to or from a particle is called “electrophoresis.” This type of separation is based on the contrarieties in conductivity or triboelectric effect of the components to be separated. On the other hand, electrical separation in which polarization is induced and no external charge transfer is involved is called “dielectrophoresis.” In this process, the separation is based on the differences in polarizabilities among minerals and other solids, which depends mostly on the environmental factors, the differences in dielectric constants, shape factors and material structures of those particles comprising the mixture. However, both electrophoresis and dielectrophoresis share the same basic mechanism; the inter-attractions between the opposite charges, or in other words, unlike charges magnetize and like charges repel one another. Some distinctions between the two phenomena are given in Table 1.3.

Dielectrophoresis

Dielectrophoresis is the translational motion of neutral matter caused by polarization effects in a non-uniform electric field (Pohl, 1951). It is important to bear in mind that the nature of neutral particles in a non-uniform field differs from the nature of those in a uniform field. In a uniform electric field, a neutral body will barely be polarized, not producing a net translation force with which the body will be pulled toward either electrode (Figure 1.1(a)). One further associated point should be made. Note that the interaction of matters in an electric field happens in two ways: as conduction or as polarization. The conduction causes a situation in which the charges that occur are free to move through the matter. If their motion is blocked or restricted, polarization will be a response description. It is believed that the most common polarization phenomenon is that which arises from the slight distortion of the centers of the positive and negative charge of the atoms. The other modes of polarization in matter are reported in the reference and will not be discussed here.

In contrary, a neutral particle acquires polarization under the influence of a non-uniform electric field, resulting in a dipole body. In this case, a negative charge in the “resultant dipole” will be put upon the side nearer the positive electrode, while a positive one on the side nearer the negative electrode. As shown in figure 1.1 (b), the unequal fields operating on the two regions in a non-uniform electric field give rise to a net translational force that drives the neutral particle, or polarizable particle, towards the strongest field region; although, the two charges on the polarized body are in fact equal. Furthermore, it does not matter which electrode is positive or negative, the force upon the neutral particle in the non-uniform field is always in the same direction. The neutral matter has a tendency to move consistently into the region of higher field intensity, if only under the influence of dielectrophoresis (Pohl, 1978).

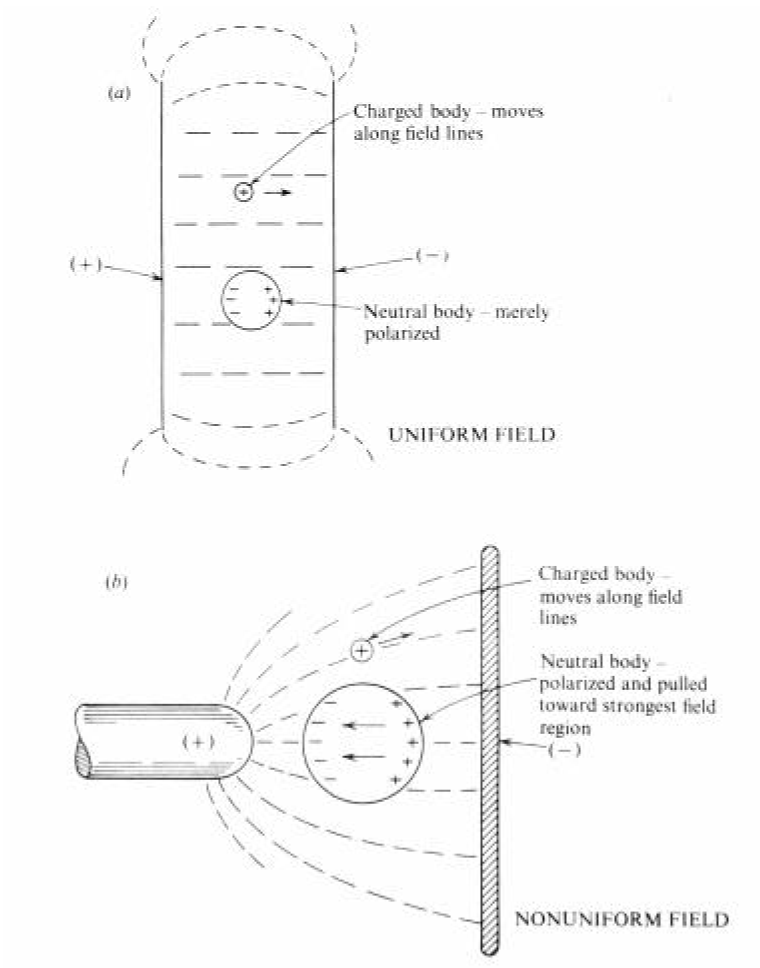

Figure 1.1. Comparison of behaviors of neutral and charged bodies in (a) a uniform electric field; (b) a non-uniform electric field (after Pohl, 1978).